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Final Report: Climate Stability: The Role of the Hydrological Cycle and the Thermohaline Circulation in the Last Deglaciation, in the Modern Climate, and in a CO_2 Warmed Climate

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I. THE PROBLEM:

It has been taken as a climatological given for many decades that Western Europe and the high latitude North Atlantic benefit greatly from an anomalously large heat transport from lower latitudes - the mean temperatures of western Europe are 4 – 5°C warmer than the same latitudes on the eastern side of the North Pacific Ocean, for example. This ocean heat transport has been described qualitatively as due to the presence of the 'Gulf Stream'; it is now known that the circulation responsible for the heat transport is more complex involving circulation in the meridional plane - the ocean thermohaline circulation.

Based on paleoclimate data from high latitudes from land, ocean and ice sheet, it is now evident that over several tens of thousands of years and up to the beginning of the Holocene, some 9000 years ago, Western Europe and the North Maritime Atlantic experienced large fluctuations of temperature on a time scale of 1-3 thousands of years which were superimposed on the slower changes associated with the growth and demise of the great Northern Hemisphere ice sheets of the last ice age. These fluctuations while not totally absent from paleoclimatic records from other parts of the world appear to have had largest amplitude in this region. Paleoceanographic data indicate large changes in the thermohaline circulation (correlated with the temperature changes), also occurred during this time, suggesting that the temperature fluctuations may have been the consequence of changes in the heat transport by the thermohaline circulation. The paleoclimate records from the Greenland ice sheet show not only termination of these large fluctuations with the beginning of the Holocene, but, in stark contrast, a remarkably stable record since. This research is concerned with identifying possible mechanisms responsible for large fluctuations in the climate of the North Atlantic environs observed in the past and for those possibly occurring in the future as a consequence of increased polar temperatures, themselves a result of a green-house induced warming. The focus is on the role of the hydrological cycle on the stability of the system.

The hydrological cycle is one of the most complicated and perhaps least understood parts of the climate system. Water is evaporated from the subtropical oceans and transported to higher latitudes where it is cooled and precipitated either as rain or snow; the precipitation may be deposited either on land, ocean or ice sheet. The water is eventually returned to its source in the ocean; this may occur within hours of the time of its evaporation or, if it falls on a polar ice cap, possibly not for thousands of years.

The process of evaporation, atmospheric transport, condensation, fallout and return to the ocean involves several critical climatological processes. In middle latitudes latent heat transport contributes the largest fraction of total latitudinal energy transport by atmospheric processes.

Water vapor, with its ability to absorb terrestrial radiation, acts as a thermal blanket over the earth's surface - the 'greenhouse effect'. This role is central to the question of global warming brought about by increasing atmospheric concentration of CO_2. An increase in CO_2, also a greenhouse gas, produces a warming which allows the atmosphere to hold more water vapor; increased water vapor content results in augmented radiative absorption and warming, and in turn, higher water vapor content - a positive feedback. Changing CO_2 concentration acts as a trigger for the water vapor-radiative-temperature feedback and the latter produces the major contribution to global warming.

A third important role of the hydrological cycle that has recently been recognized and is receiving considerable attention is its apparent control over the strength of the thermohaline circulation. Driven by latitudinal differential heating of the ocean surface, cold dense surface water in high latitudes sinks into the deep ocean and upwells in low latitudes where it mixes with downward diffusing warm water. However, net evaporation at the subtropical ocean surface effects an increase in salinity and hence density, whereas net precipitation and runoff in high latitudes decreases surface ocean density. That is, the latitudinal gradient of surface fresh water flux (out of the subtropical ocean and into the high latitude ocean) tends to suppress sinking in high latitudes and upwelling in the subtropics thereby creating a brake on the thermohaline circulation driven by latitudinal differential heating.

The cryosphere itself represents a latent dynamic component of the hydrological cycle. A change in high latitude temperature can alter the melt or growth rates of polar ice and hence alter the fresh water flux to or from the ocean. This in turn, depending on the fresh water path, may alter the rate of production of deep water and/or the latitudinal heat and salt transport by the ocean; both positive and negative feedbacks are possible.

A final important manifestation of the hydrological cycle: The circulation in the atmosphere is such that there is a continual net loss of water vapor from the Atlantic Ocean and its drainage basin and a net gain of water vapor over the Pacific. As a consequence the mean salinity and density of the Atlantic is higher than that of the Pacific. This inter-ocean density gradient apparently gives rise to the 'global conveyor belt'. The 'normal' thermohaline circulation, characterized by sinking in high latitudes, upwelling in low latitudes is modified. A considerable fraction of North Atlantic Deep Water (NADW) flows across the equator into the South Atlantic, instead of upwelling in the North Atlantic. This deep water enters the Southern Ocean and then the deep Pacific; this flow is, of course, significantly modified by mixing and by upwelling along the way. The return flow appears to be in the upper part of the thermocline back to the North Atlantic. The dramatic consequence of this altered path of thermohaline circulation is that in the South Atlantic, heat transport is directed toward the equator rather than poleward. The cross equatorial transport augments that associated with the 'normal' circulation in the North Atlantic. It is this augmented transport that results in the anomalously warm climate of Western Europe.

The objective of the project has been to determine dominant feedbacks involving ocean, atmosphere and cryosphere linked by the hydrological cycle which may exert significant control on latitudinal heat transport in the high latitude North Atlantic. This involves not only the climate stability of the late Pleistocene, but also that of the modern climate as perturbed by augmented atmospheric CO_2 concentration.

A detailed study of the hydrological cycle in the atmosphere and its linking with the thermohaline circulation of the North Atlantic Ocean is ultimately required. Such an investigation logically should involve the use of General Circulation Models (GCM) of the coupled ocean-atmosphere system (OAGCM's). Simulation of the hydrological cycle generally has been the least successful component of atmospheric GCM's (AGCM'S). Water vapor is perhaps the most difficult climate variable to simulate due, in part, to the paucity of observations over the surface of the earth, particularly over the oceans, and due also to the extreme variability of water vapor in space and time. Parameterization of clouds in the AGCM is also a major problem as discussed below. Compounding the problem for the OAGCM is the apparent extreme sensitivity of the ocean circulation to surface fresh water fluxes, i.e., the sum of runoff and precipitation minus evaporation. These problems, further augmented by the high cost of model simulations, have limited severely their use to study the stability of the climate system. For recent discussion of the problems of coupling the atmosphere and ocean heat and fresh water fluxes and of flux-adjustment procedures, see Weaver and Hughes (1996) and Marotzke (1995).

Several compromises have been attempted in order to circumvent these problems. OGCM's subject to prescribed forcing of heat and fresh water at the ocean surface have been used by themselves to examine the stability of the ocean. A variety of boundary conditions have been tried, many based on the thermal boundary conditions proposed by Haney (1971). A fundamental difference between the heat and fresh water forcing is that a perturbation in the surface temperature is normally relaxed by augmented heat exchange with the atmosphere, but a surface salinity perturbation has virtually no direct connection to fresh water exchange with the atmosphere.

Rahmstorf and Willebrandt (1995) have coupled a linearized atmospheric EBM to the ocean for improving the heat exchange with the atmosphere. Their approach resembles that first used by Birchfield (1989) for coupling an EBM to an ocean box model in which ocean surface heat and fresh water fluxes are determined by a linearized EBM with a rudimentary hydrological cycle. The Rahmstorf model, however, uses the EBM only to determine surface heat fluxes; fresh water fluxes are externally specified.

One direction of this project was concerned with the converse of the above approaches, that is, the use of a simplified ocean box model as a lower boundary condition for an AGCM. (See below.) A second direction of research here makes use of simplified atmosphere and ocean components, which allows for a full coupling between the two. Although both components are greatly simplified, compared with an AGCM or OGCM, (most obviously in the loss of spatial resolution) there was considerable preliminary evidence of internal variability between the two components in the simplified versions. See the list of publications below.

II. RESEARCH CARRIED OUT AND THE RESULTS

1. GISS Project.

Huaxiao Wang, while a graduate student at NU worked, in collaboration with the staff at GISS, on using the heat and fresh water fluxes calculated from the GISS AGCM as forcing for our box ocean component model. This was to be the first step in a full asynchronous coupling of the AGCM to the ocean box model. The purpose was to use the ocean box model as an improved mechanism for obtaining ocean heat fluxes as a lower boundary condition for the AGCM. A number of experiments were completed both for the modern climate and for the simulated climate with doubled CO_2. One consistent feature of the doubled CO_2 simulations was the reduction in production of NADW in the North Atlantic; this was as a consequence of a stronger latitudinal transport of water. Manabe and Stouffer (1994) have shown that in a fully coupled OAGCM experiment, increasing atmospheric CO_2 level indeed reduced the strength of the thermohaline circulation by augmented fresh water flux into the polar source regions from an intensified hydrological cycle. The effects would have been more pronounced if the melt water from melting polar ice caps had been included.

The development of coupling of the GISS AGCM to the ocean box model was interrupted when H. Wang took a post-doctoral position at the U. of South Carolina. It simply was not possible for him to continue there with this project. In addition, I had received, on short notice, an invitation to be a visiting professor for a year at Laboratoire Meteorologie Dynamique (LMD) in Paris. Although these events made it impractical to continue the coupling to the AGCM we were able to continue with the fundamental project of identifying possible feedbacks controlling the stability of the ocean heat transport in the N. Atlantic.

2. Multi-component Model Development

Our objective was to simulate using simplified multi-component models, feedbacks between the hydrological cycle, the thermohaline circulation and the polar ice caps for Pleistocene, modern and global-warming scenarios. Although our initial multi-component model development was successful in many respects (see the papers listed below), it became evident at about the time I went to Paris, and H. Wang left for U. South Carolina, that certain additions or improvements were highly desirable.

a. It was deemed necessary to improve the parameterization of the advection-diffusion mechanism appropriate for ocean box model simulations.

b. The elements of ocean carbonate chemistry were needed, again on a level of complexity consistent with that of the ocean box model, in order to simulate the full cycle of the feedbacks between the carbon chemistry of the ocean and atmospheric pCO_2.

c. In AGCM's changing atmospheric pCO_2 is calculated directly through its effect on terrestrial radiation. In a conventional atmospheric energy balance model this is not possible without making a host of questionable assumptions. A new direct way of incorporating the atmospheric radiative effects of pCO_2 changes was needed.

d. The slow insolation forcing background for the rapid climate variability associated with the demise of the great ice sheets comes from changing precession and obliquity. The precessional effects are thought to be of particular importance in the deglaciation process. In order to adequately simulate the effects of precession, it is necessary to simulate the seasonal cycle. For adequate simulation of ocean-atmosphere fluxes with a seasonal cycle, a surface ocean mixed layer is required. More difficult, but nevertheless needed with the seasonal cycle is a thermodynamic model of sea ice of maximum simplicity.

e. Although not of essential importance on the deglaciation time scale, it was apparent that an improved lithosphere-asthenosphere model was needed for interaction with the ice sheet component of the model. A new mass balance equation at the surface of the ice sheet and a revised ice sheet model which is quasi-three dimensional was felt to be highly desirable.

The work implied in the above is described below in somewhat more detail.

a. Advection-diffusion algorithms: The estimation of advection and eddy diffusion of heat and salt is a fundamental problem in formulating a coarse resolution ocean box model. This difficulty is an important limitation on the usefulness of ocean box models. There are two contrasting numerical methods: the 'upstream' advection and the 'centered' advection schemes. Both have severe limitations. The former, which requires the assumption that each box is well mixed, has an inherent very large and purely numerical diffusion built into it; it is so large that it may well mask essential model response. The 'centered' approach can under certain circumstances give rise to unrealistic local interior extrema. In our original ocean model, the latter has been used. Most ocean box model studies have used the 'upstream' method. Most numerical finite difference models have used the 'centered' method. I have now generalized the numerical algorithms used by Wright (1992) and Wright and Stocker, (1991). These approaches are based on earlier work by Fiadeiro (1975) and involve integration of the advection terms across the interface between each pair of adjacent ocean boxes. I have extended the previous work by including explicitly the time variability of the fluxes. The new method, in effect, is a combination of the two limiting methods; the weighting of the two depends on the relative strength of advection to diffusion at each interface. The algorithms are more complex but take little more computing time than the limit schemes.

b. Ocean carbon chemistry: With the aid of Prof. David Hollander we have incorporated the elements of carbon chemistry into the ocean box model and introduced new dependent variables for each ocean box: total dissolved carbon (TDC) and alkalinity (ALK); the structure for including phosphate and oxygen concentration has been included but has not been used yet. With the inclusion of the rudiments of the biological pump, an additional parameter is the bioproductivity in each surface box. In addition to control by the chemical equilibrium equations, the TDC and ALK are advected and transported by eddies between ocean boxes in the same manner as heat and salt. Since the ocean, except for the mixed layers, is run without a seasonal cycle, there is no seasonal cycle of pCO_2 in the atmosphere or the mixed layers; it is assumed that atmospheric pCO_2 is spatially uniform, the rate of accumulation being simply the net flux from the surface ocean boxes into the atmosphere.

c. pCO_2 changes and long wave radiation: With the aid of Drs. Laurent Li and Herve LeTreut at LMD, Paris, we have utilized the radiation code from the LMD AGCM to develop an explicit treatment for both short and long wave radiation appropriate for our simple atmospheric energy balance model. The EBM has only one layer, that is, the temperature profile is completely determined by the surface air temperature and lapse rate. The surface air pressure is known and a relative humidity profile is assumed. The fluxes of long and short wave radiation at the top of the atmosphere and at the surface of the earth are required. For each of these we simply fit a multi-dimensional polynomial to the 'true' radiation flux as calculated by the AGCM radiation code. The latter is very complex and time consuming; the polynomial is simple and computationally fast. It is, however, limited by the range of each of the independent variables which must be specified in order to carry out the least squares fitting procedure. Maximum and average errors of each radiative flux are found to be well within reason for a simple one layer model. The radiative flux polynomial is not only a function of atmospheric pCO_2 but also of other important variables, including surface temperature, surface air temperature, lapse rate, surface albedo, surface relative humidity, surface pressure, and, importantly, parameters describing clouds: cloud fraction; emissivity and optical thickness.

For simplicity only the pCO_2 and the surface variables need be considered as variables, the others being specified climatologically. These variables offer, however, rich opportunities for sensitivity studies. The role of the cloud parameterization, in particular, is discussed below.

d. Atmospheric seasonal cycle: The seasonal cycle is simulated only for the atmosphere and for the mixed layer boxes of the ocean. The atmosphere now consists of four zonally averaged boxes: N polar, N tropical-subtropical, S tropical-subtropical and S polar. Underlying the atmosphere and on top of each ocean box, lies an ocean mixed layer box. The seasonal cycle of sea ice is important in two respects; first it has a major effect on the surface albedo; secondly it has a direct control on the exchange of sensible heat and water vapor with the atmosphere.

e. Ice sheet-bedrock models: With the aid of a student and Dr. Yannick Ricard in Paris, a new earth response model has been incorporated into the climate model. As a first step this model still computes deformation of the earth's surface only for a zonal or 2 dimensional ice sheet loading. The conversion to a 'quasi- three dimensional' deformation earth model is not a big step beyond the present new model. The new model has a great deal of flexibility in that the viscosity profile of the asthenosphere can be prescribed in as much complexity as desired. The present version has been chosen to have an 80 km deep elastic lithosphere overlying a uniform viscosity asthenosphere. Together with the quasi-3D earth model, a scheme has at least been sketched for modifying the ice sheet model code to be quasi-three dimensional. The scheme for both the earth and ice sheet models achieves 'three dimensionality' by assuming a meridian of symmetry for both ice sheet and earth models. This scheme requires a new algorithm for mass balance at the surface of the ice sheet which has only been sketched out at this point. The basic numerical methods used to extrapolate the ice sheet thickness have also been completely revised.

3. Current Status of the Model

It has taken more than two years to incorporate the changes described above. We are presently testing the components and making preliminary simulations with the completely coupled model. A brief summary description of the model follows.

a. Atmosphere:

The EBM is made up of four latitudinally arranged boxes conserving energy, air mass and water. In each box the atmosphere is a single layer with constant lapse rate up to 200 mb, isothermal above. For determination of radiative fluxes, there is an assumed vertical profile of relative humidity, two layers of prescribed clouds, together with surface air temperature, surface air pressure (determined by the mean elevation of land, including the ice sheet if present), surface albedo and atmospheric CO_2 concentration. In each box there is a balance of vertical fluxes of long and short wave radiation at the top and bottom of the atmosphere, latent and sensible heat flux exchange at the surface averaged over the surface of the box, eddy heat exchange with the adjacent latitudinal boxes and a storage term. Water mass conservation is a balance of evaporation from the surface, precipitation and a temperature dependent storage term and eddy exchange with adjacent boxes. Precipitation is determined as the residual of the other water sources, including horizontal exchange with adjacent boxes. Latitudinal transport of water vapor is proportional to evaporation and to the latitudinal temperature gradient.

b. Ocean:

The ocean model consists of the North (including the Arctic), South Atlantic, the Southern, the North and South Indian, and the North and South Pacific Oceans. It is made up of 9 surface mixed layer boxes (MLB) and 9 upper and deep ocean boxes. Heat, salt and water mass are conserved in each box. The MLB comprise the upper part of the upper ocean boxes. Heat, fresh water, and CO_2 are exchanged with the atmosphere and the MLB. Together with the atmosphere, the MLB and the parameterized sea ice extent are extrapolated over the seasonal cycle. Energy and salt (fresh water) balance for the upper and deep ocean boxes is made up of a storage term, the net horizontal and vertical advective-diffusive fluxes and exchange with the atmosphere. Advective-diffusive fluxes between the MLB and upper ocean boxes are interpolated from the fluxes at the large box interfaces.

c. Carbon Chemistry:

Carbonate equilibrium equations are formulated for extrapolating on the mean annual scale the TDC and ALK in each box (see below.) Rudiments of the biological pump are incorporated; rates of bioproductivity are specified input parameters in the current version. TDC and ALK are advected-diffused between boxes in the same manner as heat and salt. In the MLB CO_2 is exchanged with the atmosphere by a temperature dependent flux equation.

d. Ice Sheet - Bedrock:

The present version has a zonally averaged ice sheet with elevation dependent on latitude and time; dynamics is governed by a power law rheology. Mass balance at the surface is controlled by the assumed lapse rate in the atmosphere and mean surface air temperature of the high latitude box. Positive mass balance removes water vapor from the high latitude atmospheric box; negative mass balance puts melt water into either the high latitude or low latitude surface North Atlantic box. The bedrock deformation under ice loading is calculated with a perfectly elastic lithosphere and the asthenosphere presently consists of a single layer of uniform viscosity; a liquid core is assumed.

e. Extrapolation procedure:

The atmosphere-ML are extrapolated on the seasonal time scale. After a block of years extrapolation of this model, the ocean box model is extrapolated one step over the same block of years, after which another block of atmosphere-ML extrapolation is made: After a block of years of ocean extrapolations, one extrapolation is made of the ice sheet bedrock model over this same period, using the mass fluxes calculated from the atmosphere and ocean extrapolations. In other words, the model is synchronous in time. For very long extrapolations this procedure can be relaxed if need be.

4. Preliminary Results

Experiments indicate that the spurious numerical diffusion in the ocean box model component is now significantly reduced compared with that in 'upstream' algorithms; no evidence of unrealistic interior extrema has been found with the new advection-diffusion algorithm.

Simulations have been made with the atmosphere-mixed layer model without coupling to the deep ocean and ice sheet components. In particular, sensitivity to doubling of atmospheric pCO_2 has been tested. Results have been informative in several respects. First, with no sea ice in the model, global warming is found to be approximately 1°C, about 1/4 of what is typically found in AGCM's. This is true for both the case of no clouds and for fixed nonzero cloud amounts. With the inclusion of a preliminary parameterization of sea ice and its effect on the surface albedo, global mean temperature increases 1. 8°C, about 1/2 of the AGCM value.

Why is the model yielding substantially lower sensitivity compared to the AGCM? More conventional EBM's have much more highly parameterized radiation physics than the model here and can be tuned to yield almost any reasonable value of model sensitivity. This is not easily done in our model. The answer to the question most likely lies in ascertaining what feedbacks are important for amplification of the CO_2 induced warming. Two of these are: the water vapor-radiation temperature feedback and albedo-temperature-radiation feedback. The first is fully incorporated in the model. At this point the model surface albedo is variable over the oceans, i.e., through sea ice variablity, but not over land. It has been thought that the sea ice was more important than the land to model sensitivity. Variable land surface albedo is presently being added and is a relatively simple model enhancement.

The most important class of feedbacks present in most recent AGCM'S but absent in our EBM are cloud-radiation feedbacks. Clouds interact both with incoming solar and outgoing terrestrial radiation in a number of complex feedbacks. The simplest view of the role of clouds in climate sensitivity is one of competing feedbacks: increasing clouds increases the planetary albedo and cools the atmosphere, while at the same time increasing absorption of terrestrial radiation, thus warming the atmosphere. Early versions of cloud simulation did show an approximate cancellation. (See Wetherald and Manabe (1980)). More recent cloud parameterizations yield cloud feedbacks which tend to increase climate sensitivity overall. (See Wetherald and Manabe (1988) and Le Treut et al (1994)). The enhancement comes about from a decrease in low cloud amount for doubled pCO_2 and an increase of high clouds at the tropopause. Both effects tend to warm the atmosphere, since the optical thickness of the high clouds is so low, the increased albedo effect is more than compensated for by the lowering of the effective temperature of terrestrial radiation to space. LeTreut et al (1994) estimate relative contributions from the various climate feedbacks including cloud feedbacks. In general, although different parameterizations alter the relative importance of the feedbacks, clouds appear to operate as a net positive feedback in the doubling of pCO_2 simulations and may have a larger contribution than the albedo feedbacks.

Our model clearly was not designed to be a vehicle for studying the role of cloud parameterization schemes on climate sensitivity. However, with the introduction of highly simplified but explicit effects of changing atmospheric CO_2 on the radiation calculations, the radiative physics is now sufficiently sophisticated that parameterizations of cloud variability appear necessary, at least if comparable sensitivities to the AGCM are to be achieved. Although this is a complicating issue for our coupled model, it is important and satisfying to see that such a simple model of the atmosphere now has the capability to explicitly include feedbacks which have been found to be important in AGCM simulations of climate sensitivity.

5. Applications of the Coupled Model Two important applications of the fully coupled ocean-atmosphere-ice sheet model set forth above are to 1) simulate the last deglaciation and to 2) simulate the doubled pCO_2 global warming scenario. To our knowledge this greatly simplified multi-component model is the first (of any complexity) that includes all of the rudiments of the physics and chemistry of the pCO_2-ocean-circulation-ocean-chemistry feedbacks.

There is no aspiration to obtain definitive answers with the coupled model as to which feedbacks play the most important roles in these two climate events, one which occurred in the past and the other which may occur in the future. However, there certainly exists an exciting opportunity to determine the sensitivity of the model climate system to the many (albeit highly parameterized) multi-component feedbacks and to thereby gain a first cut understanding of which are most important.

One must not loose sight of potential limitations imposed by the simplicity of the model system relative to that of the prototype. The usefulness of the box model is at the heart of the exercise. Historically the box model has proven to be of most value in isolating essential physics and thereby aiding the understanding of the system being investigated. See for example, Stommel (1961). More recently Rahmstorf (see for example, Rahmstorf (1995a)) has made an elegant use of an ocean box model to explain - one could almost say, to confirm - the simulations of the stability of the thermohaline circulation with his global OGCM.

Simulations of Rahmstorf (1995b) and work by others, raise a potential limitation to the applicability of the low resolution box model. He shows that if the fresh water flux is perturbed in the Greenland-Iceland-Norwegian (GIN) Sea, it is possible to shut down production of NADW there, but to see it start up at nearly the same rate in the Labrador Sea region further south. Since the deep water being produced in the new region is warmer than that produced in the GIN Sea, it sinks to a shallower depth and, most importantly, the net flux of heat to the high latitude N. Atlantic is dramatically reduced, since the flux is proportional to the difference of temperature of the surface inflow and deep outflow. In the large boxes commonly used in an ocean box model, such shift of source regions is not detectable. Because of the unrealistic nature of the fresh water flux boundary condition in the OGCM it remains uncertain how robust such a shift mechanism is.

On the other hand, there appears to be further evidence as to the validity of the box model approach to be coming from recent work of Rahmstorf, as yet unpublished, concerning the mechanism of the 'global thermohaline circulation'; his results appear to confirm those reached by Wang et al.(1992) which came from using our original box ocean-atmosphere coupled model.

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V. STUDENT EDUCATION:

Huaxiao Wang worked actively on parts of the project; he received his doctorate in 1993 and is now in a climate modeling group at Lawrence Livermore Laboratory in Livermore, CA.

Jonathan Rich is in his fifth year of graduate studies. He has contributed heavily to the multi-component model development; he has, for example, developed the atmosphere-mixed layer model largely by himself. He should be finishing his doctoral studies within a year.